FINAL REPORT

Great Earthquake Recurrence Statistics Along the Cascades Subduction Zone: Collaborative Research with Earth Scientific Consultants, Inc. and the U.S. Geological Survey

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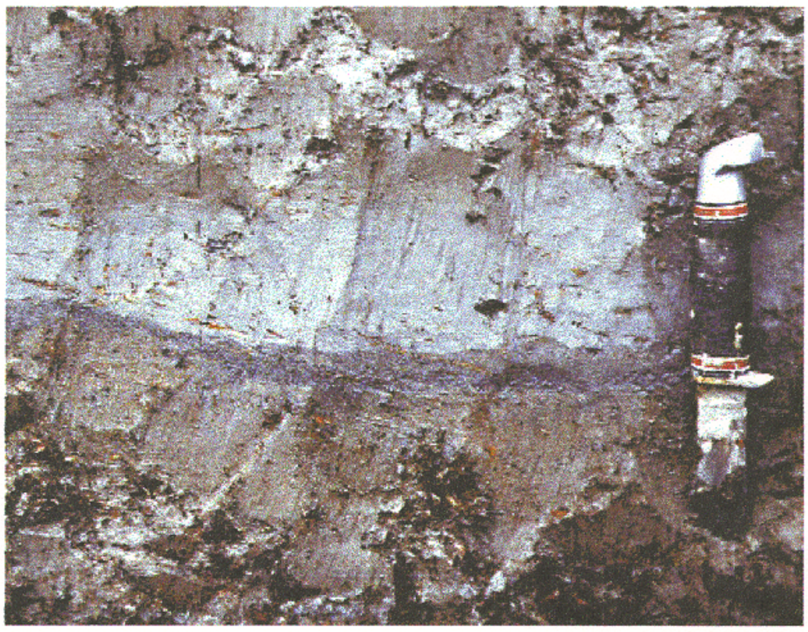

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Executive Summary

- Participation in 1997 field season, conducted stratigraphic surveys, sampling of material for radiocarbon dating as well as tree sampling to confirm the January 1700 earthquake and document forest renewal times.
- Collected published paleoearthquake chronologies for 20 sites along the Cascades subduction zone. All sites record the 1700 AD earthquake, many record two additional widespread events in 1700 ybp and 2400-2700 ybp. Between these three great events, evidence for other events that may represent large or moderate magnitude intra- and interplate earthquakes.
- Use data from southern Washington to develop probabilistic estimates of seismic hazard with in the next century. Recognition and quantification of the uncertainty in our estimate is an important component to developing a realistic seismic hazard assessment for the Cascade subduction zone. While our best, unbiased estimate (0.25 in 50 years) is associated with a large uncertainty (0.04 to 0.57) it does provide a valuable baseline for future scientific research and public safety and engineering decisions.

Introduction

Earthquakes of M>8 or larger pose a recently discovered threat to the northwestern United States and southwestern Canada (Atwater et al., 1995). Coastal geologic investigations conducted during the last decade as part of the National Earthquake Hazard Reduction Program (NEHRP) have established a paleoseismic chronology along coastal British Columbia, Washington, Oregon, and California during the last 3800 years. The combined evidence for land level changes, tsunamis, and strong ground shaking demonstrates that earthquakes of magnitude 8 or larger have occurred on the boundary between the overriding North American plate and the subducting Juan de Fuca and Gorda plates.

Determining the recurrence behavior of these great subduction earthquakes is a critical element for seismic hazard assessment in the northwestern United States. The results of these investigations directly impact the development of national and regional seismic risk maps, building codes, and emergency planning and mitigation activities at the community, county and state levels.

Until recently, estimates of recurrence intervals and long-term probabilities for great earthquakes at the Cascades subduction zone were poorly known because of uncertainties in the number and ages of earthquakes (Atwater et al., 1995). New high precision radiocarbon dates, coupled with regional microfossil and stratigraphic correlation of buried soils, and tree ring dating have begun to improve the space-time chronology of great earthquakes in this region. The most recent event, about 1700 AD, has been correlated over 900 km from southern British Columbia to northern California (Nelson et al., 1995) using these techniques. In addition, tsunami records from Japan indicate an event in January 1700 that may be best explained by the occurrence of a great earthquake at the Cascade subduction zone (Satake et al., 1996).

In southern coastal Washington, seven events in the last 3500 years can be correlated for a distance of 100 to 200 km (between the Copalis and Columbia River sites in Figure 1). (Atwater et al., 1998). While the average time between these events range from 500 to 540 years, the intervals between individual events range from a few centuries to about 1000 years. The factor of ten range in repeat times does not suggest the same type of quasi-periodic recurrence behavior that has been postulated for great subduction zone earthquakes at many plate boundaries (i.e. zones that have been used a tectonic analogs for the Cascades subduction zone (Heaton and Hartzell, 1987, 1989), such as southern Chile (Nishenko, 1985) and southwest Japan (Ando, 1975)).

As the recognition of paleoearthquakes along the Cascades subduction zone improves, we need to address how these events are distributed in space and time. For example, with the exception of the most recent event in 1700 AD, the rupture dimensions are not well known for these earthquakes. It is not known if all seven events in southwestern Washington represent single giant ruptures or a series of overlapping multiple ruptures, whose characteristics change from cycle to cycle (e.g.., Thatcher, 1990). Do they occur quasi-periodically (as has been observed for many circum-Pacific plate boundaries (Nishenko, 1991) or do they tend to be clustered in time? Does the occurrence of the most recent event in 1700 AD signal the beginning of a new episode or 'active' period of subduction in southern Washington. Is there evidence for segmentation of the Cascades subduction zone based on the paleoseismic history? How does this segmentation compare to tectonic models that have been proposed for the region?

To help answer some of these questions, and improve our understanding of great earthquake occurrence along the Cascades subduction zone, three tasks were identified for investigation by Earth Scientific Consultants, Inc. in this collaborative research project with Drs. Brian Atwater and Alan Nelson of the US Geological Survey-

- Improve the age determinations of key paleoearthquakes
- Identification and mapping of paleoearthquakes along the Cascades subduction zone
- Improve recurrence models and refine earthquake probability estimates

Project Task 1 - Improve age determinations of key paleoearthquakes

Three activities were conducted during the 1997 field season to fulfill this project task–

1. Stratigraphic surveying and collection of organic material for high-precision radiocarbon dating.
2. Tree sampling to better document the proposed January 1700 Cascadia earthquake.
3. Tree sampling to document forest renewal times after the January 1700 earthquake.

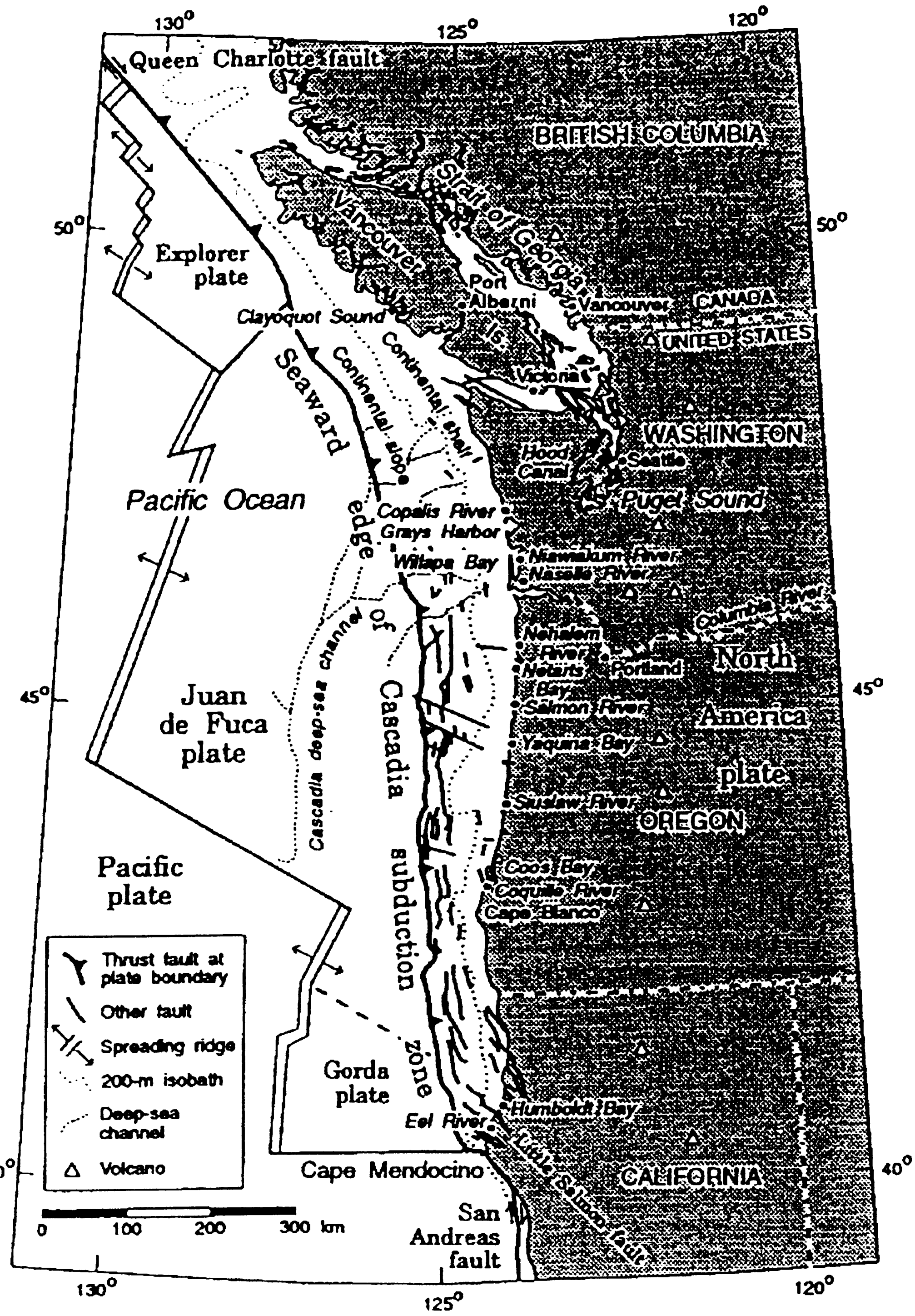

Figure 1 Cascadia Subduction Zone. Map shows place names, plate boundaries, and recently active faults within the North American plate. Barbs denote the dip of the plate-boundary thrust, which extends eastward beneath the coast. Faults shown have been active in the past two million years.

1. Stratigraphic surveying and collection of organic material for high-precision radiocarbon dating.

Estuarine stratigraphy is the basis for the majority of earthquake recurrence studies in Cascadia. A two-week program of outcrop investigation and coring concentrated on collecting samples to improve the age dates of events that had already been identified by Atwater (199). During July 1997, Juan Carlos Moya was hired by Earth Scientific Consultants Inc. to participate in a field party, headed by Dr. Brian Atwater, that surveyed the stratigraphy of intertidal outcrops at the following estuaries (see Figure 2 for locations) -

- Columbia River – two outcrops along the Lewis and Clark River near Astoria, WA
- Willapa Bay – one outcrop along the South Fork Willapa River near Raymond WA
- Grays Harbor – two outcrops along the Chehalis River, near Aberdeen
- Puget Sound – one outcrop along the Snohomish River, near Everett; another near the Duwamish River, in Seattle

Results from this fieldwork are still far from publication. High-precision radiocarbon ages for three cases (discussed in the next section) only became available during August-October 1998. Since that time, Dr. Atwater, project co-investigator, has been on travel to Japan. These outcrops join several dozen others that have been investigated as part of a longer-term study of Holocene earthquake stratigraphy.

Stratigraphic surveys conducted during the 1997 field season provided context for several new radiocarbon dates of uncommonly high precision for three earthquakes. Two of these events are part of the lettered series documented in USGS Professional Paper 1576. The ages are given in conventional radiocarbon years, before AD 1950, followed by their lab identification number.

3177 ±16 (QL – 4919)
Stratigraphy: about 50 tree ring years before event J, South Fork of the Willapa River.
Age is measured on tree rings 48-54 of an earthquake killed spruce, where ring 1 adjoins the bark. This is only the third site to date that has yielded a high-precision age on event J, and only the second site where an age comes from an earthquake killed tree. All of these sites are at Willapa Bay, and all the ages are concordant.

1227 ±30 (QL-4924)
Stratigraphy: shortly after event U, Lewis and Clark River.
Age measured on the below ground stems of a plant, *Triglochin maritima*, that colonized a post-earthquake tidal flat near Astoria, Oregon. This age provides the first strong radiocarbon evidence that event U is recorded at the Columbia River estuary.

336 ± 15 (QL – 4936)
Stratigraphy: shortly after an unnamed earthquake in Seattle along the Duwamish River. This earthquake caused liquefaction, recorded by dozens of dikes at the surveyed outcrop. Some of the dikes are connected with horizontal lens of sand that represent the flanks of vented-sand volcanoes. The dated material consists of the tubers of tidal-marsh plants that grew into mud 0-10 cm above one of these lenses. The age shows that the liquefaction predates the 1700 Cascadia earthquake by 50-150 years. This finding argues against an interplate source for this event. Instead, it may represent an intraplate event within either the subducted Juan de Fuca plate or within the overriding North American plate.

Large uncertainties in the timing of event L (2200-3800 ybp @0.95 CI) affect repeat time estimates between events J to L and L to N in southwestern Washington. Current estimates for event L are based on conventional radiocarbon ages from five localities in Grays Harbor and Willapa Bay, WA. Resolution of this event can be improved by the use of high-precision radiocarbon dating. A similar situation exists for event W (900 – 1300 ybp @0.95 CI), as well. Five additional high-precision ages have been measured on spruce roots in soil L. (Atwater, personal comm., 1998) used previously collected samples and additional samples collected in August 1997. Atwater (personal comm., 1998) has also made improvements in the dating of soils N (one high-precision age) and W (one conventional age based on material sampled in 1998).

2. Tree-Ring Dating of the 1700 Cascadia Earthquake

Tree ring data tends to confirm that a January1700 tsunami, known from written records in Japan, resulted from the most recent great earthquake at Cascadia. The dating, from four estuaries in southern coastal Washington, shows that the earthquake occurred in the months between August 1699 and May 1700 (see attached reprint - Yamaguchi et al., (1997); Jacoby et al., 1997). Juan Carlos Moya helped to sample the trees that gave this result (see Table 1 of Yamaguchi et al., (1997)). Moya also sampled other trees during the 1997 field season to check published dating. The tree ring pattern matching for these trees is still in progress.

3. Tree-Ring Measurements of Earthquake Recurrence Intervals

Tree-ring counts have the potential of reducing uncertainty in estimates of recurrence intervals less than 400 years for great plate-boundary earthquakes at Cascadia. For centuries long recurrence intervals, uncertainties in radiocarbon ages can yield overlapping age ranges for the two successive earthquakes. Counts of rings in trees that live entirely within the interval, and were killed by the interval that ended it, can provide non-zero estimates of the intervals minimum length.

In support of this tree ring approach, the 1997 field party made tree-ring counts of Sitka spruce that have lived entirely within the present recurrence interval, since the 1700 Cascadia earthquake. We wanted to learn how much time elapsed between the 1700 earthquake and the re-establishment of tidal forests at various places along estuary salinity gradients. Such forest renewal time can be added to ring counts of earthquake killed trees to obtain a closer tree-ring approximation of the lengths of past recurrence intervals.

The 1997 tree-ring work was done along the Chehalis River, the main tributary of Grays Harbor. It filled the main hole in a more comprehensive tree-ring study done in 1992 by Boyd Benson and several coworkers. Moya assisted in preparing the tree cores for counting, and making some of the counts. A manuscript describing the tree-ring counts from the post-1700 forests is currently in preparation by Atwater et al.

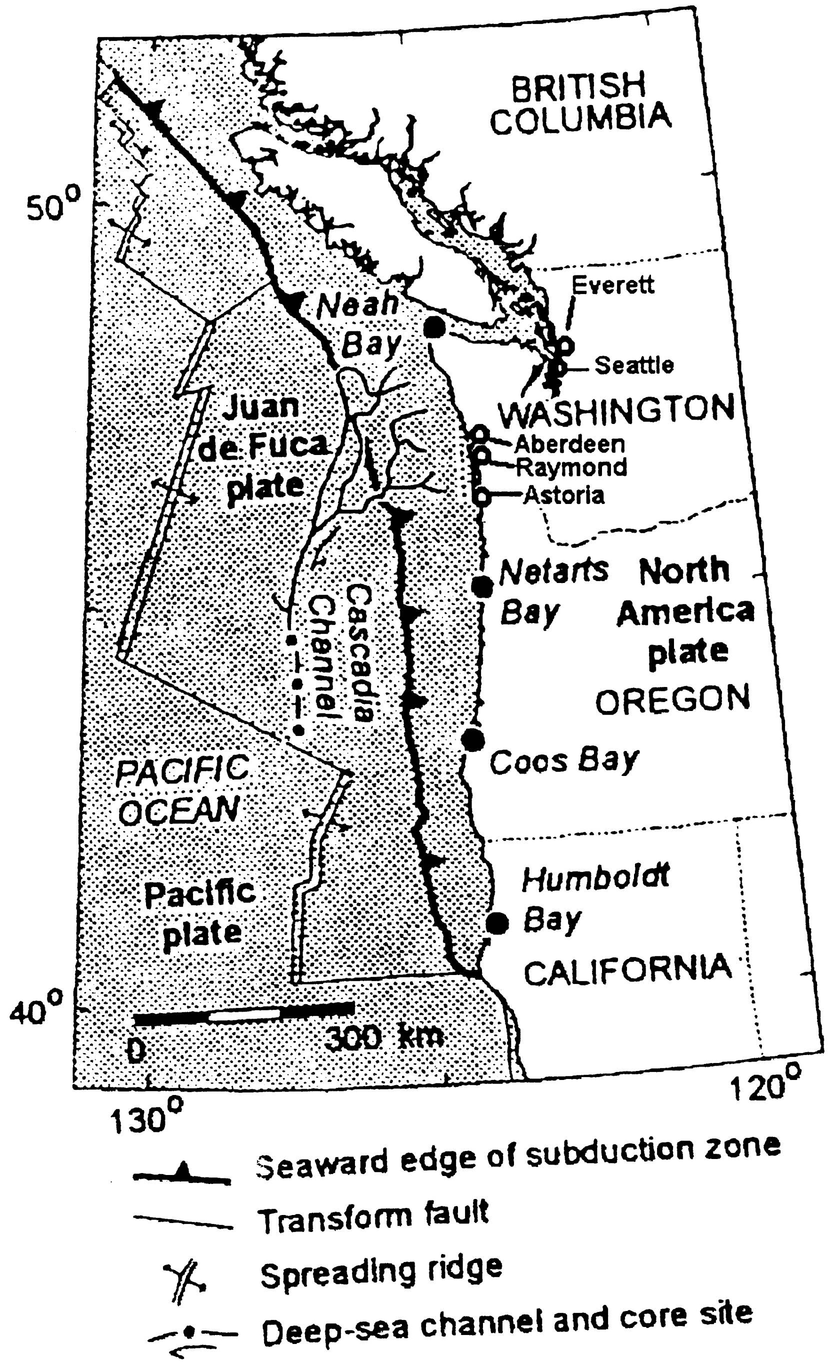

Figure 2 1997 Field Season sites. Map shows locations of estuaries visited during July 1997 field season. These include sites at the Columbia River – two outcrops along the Lewis and Clark River near Astoria, WA; Willapa Bay – one outcrop along the South Fork Willapa River near Raymond WA; Grays Harbor – two outcrops along the Chehalis River, near Aberdeen and Puget Sound – one outcrop along the Snohomish River, near Everett; another near the Duwamish River, in Seattle.

Project Task 2 – Identification and mapping of paleoearthquakes along the Cascades subduction zone

The coastal extent of buried soils and inferred earthquake ruptures is one of the central issues in Cascades paleoseismology. This Project Task addresses the stratigraphic correlation of paleoearthquakes along the northwestern coast of the United States from Vancouver, British Columbia, through Washington, Oregon and northern California.

We have collected published paleoearthquake chronologies for 20 sites along the Cascades subduction zone to examine the space-time distribution of great (and large) earthquakes. Unless noted, the data shown in Table 1, are presented in terms of radiocarbon years before present (AD 1950). The height of the boxes is equal to the ± 1 sigma uncertainty.

Complexities in coastal wetland stratigraphy due to differences in regional geology and tectonics, morphology, sediment supply, wetland surface elevations, preservation potential, types of material dated and quality/type of 14C age determination as well as variations in the actual recurrence patterns of earthquakes make identification and correlation of individual events difficult. Regional variations of the zero-isobase line for geodetic deformation associated with great earthquakes affect the presence and location of submergence sites (Nelson and Personius, 1996; Peterson and Darienzo, 1996)
The majority of the sites sampled in this study are north of Coos Bay (see Figure 1). Few sites are located south of Cape Blanco, in southern Oregon and northern California. High gradient rivers in this region have predominately sand and gravel sedimentation and offer few marsh areas to record coseismic sea-level changes.

A number of researchers, including Darienzo, Peterson and Clough (1994) and Nelson et al. (1996) have suggested criteria for the unequivocal identification of coseismic subsidence or burial events due to great plate boundary earthquakes along the Cascades subduction zone. These criteria include -

- Peat overlain by a distinctly sandy horizon, overlain by sediments with a lower organic content than the peat - *a standardized stratigraphy* that includes evidence for -
- Suddenness and amount of submergence – *abrupt burial contact*
- Lateral extent of submerged tidal-wetland soils – *lateral correlation*
- Coincidence of submergence with tsunami deposits – *distinct sandy deposits*
- Degree of synchroneity of submergence events at widely spaced sites - *regional correlation*

The next section contains a brief discussion of the data used to develop the space-time diagram in Table 1. Detailed descriptions of the geologic setting and stratigraphy can be found in the original references.

Vancouver, BC

- Annacis Island
  Clague et al., (1997)- weighted mean AMS date @ 1763 ± 42 rcybp [calendar date of 1542-1815 ybp @ 2 sigma].

- Port Alberni
  Nelson et al., (1995)- High-precision ages on rhizomes and organic material in tsunami deposited sands: 145 ± 12 and 261 ± 14

Washington

- Copalis River
  Nelson et al., (1995) – High-precision weighted mean ages on tree rings: 1 year before tree death -138 ± 17 yrs.; 5 years before tree death 112 ± 11 yrs.; 40 years before tree death- 207 ± 9 yrs.; AMS ages on rooted leaves and stems- 139 ± 17.

- Niawiakum River
  Nelson et al., (1995) - High-precision weighted mean ages on tree rings: 40 years before tree death – 210 ± 9 yrs; 60-80 years before tree death – 301 ± 10 yrs; AMS ages of rooted leaves and stems – 161 ± 15 yrs.

- Grays Harbor
  Shennan et al.,(1996) - 8 events in 5000-5400 years, average 670-730 years

- Willapa Bay
  Atwater and Hemphill-Haley (1997) – soil Y – January 1700; soil W- 900 to 1300 yr bp; soil U- 1130 to 1350 yrbp (based on high-precision ages (1260 ± 14 and 1300 ± 25 yrs); soil S – 1500 to 1700 yrbp (based on high precision ages of rhizomes and tree rings); soil N –2400 to 2780 yrbp. (based on high-precision ages of forest floor litter (2475 ± 23 yrs); soil L – 2800 to 3300 yrbp, ; soil J – 3320 to 3500 yrbp. Figure 3 shows the geologic and stratigraphic evidence for these events in Willapa Bay.

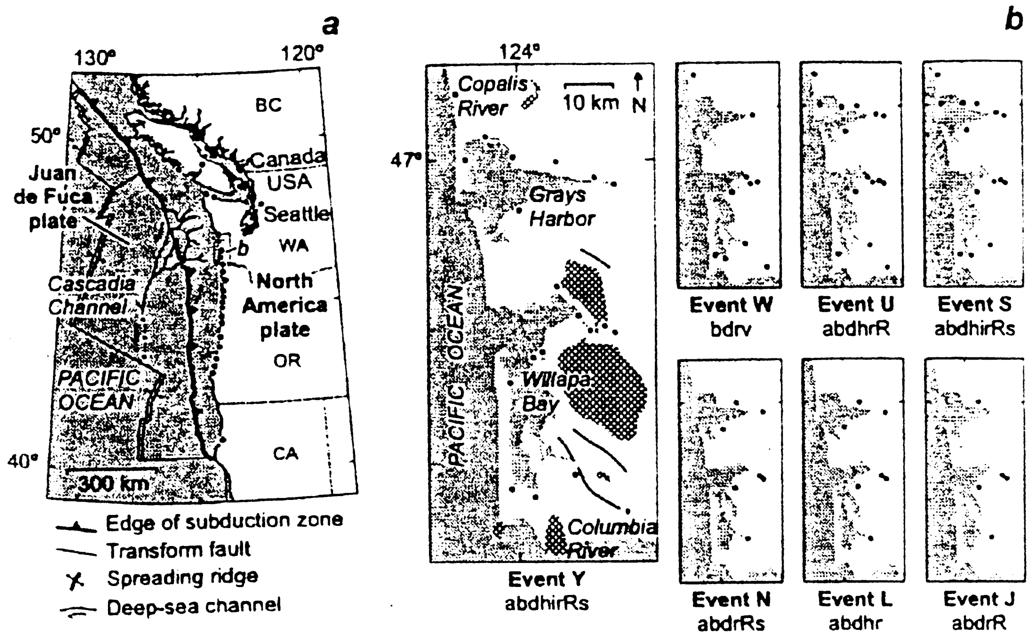

Figure 3 Evidence for great earthquakes in the past 3500 years in southern coastal Washington. **a)** Regional location map **b)** Detailed map of Grays Harbor and Willapa Bay. On map for soil Y, dashed areas are structural highs marked by Eocene Crescent Formation, and black lines are synclines mapped in rocks as young as Miocene (Walsh et al., 1987). Each dot denotes a buries soil observed in one or more surveyed outcrops at least 15 m long (•) as described in Atwater (1992) and Atwater and Hemphill-Haley (1996) or (O) from unpublished work by B.F. Atwater. **a**, remains of herbs rooted in mud above buried soil and typical of low parts of tidal marshes (Atwater, 1992; Atwater and Hemphill-Haley, 1996; Atwater and Yamaguchi, 1991); **b**, remains of trees or herbs rooted just below top of buried soil and typical of high parts of tidal wetland or of upland (Atwater, 1992; Atwater and Hemphill-Haley, 1996); **d**, contrasting diatom assemblages indicating that mud above the soil accumulated at lower altitude than did the soil itself (Atwater and Hemphill-Haley, 1996; Hemphill-Haley, 1995; Shennan et al, 1998; Ota and Umitsu, 1995); **h**, herbaceous stems and leaves rooted in buried soil and entombed by tsunami and/or tidal-flat deposits above it (Atwater, 1992; Atwater and Hemphill-Haley, 1996; Atwater and Yamaguchi, 1991); **i**, sand intrusion probably due to liquefaction and lateral spreading during subsidence; **r**, conventional radiocarbon age (Atwater, 1992; Atwater and Hemphill-Haley, 1996; Shennan et al, 199..); **R**, high-precision radiocarbon age (Atwater and Hemphill-Haley, 1996; Atwater et al., 1991); **s**, sandy layer on buried soil, probably deposited by tsunami (Atwater, 1992; Atwater and Hemphill-Haley, 1996; Reinhart and Bourgeois, 1987); **v**, vented sand of enigmatic but probably seismic origin (Atwater, 1992).

- Naselle River
  Nelson et al., (1995) – AMS ages on rooted leaves and stems – 162 ± 16 yrs.

Cascadia Channel

Adams (1990, 1996) , Griggs and Kulm (1970), Griggs et al., (1969)
Recurrence intervals recorded by buried soils in southern Washington have been suggested to resemble recurrence intervals recorded by offshore turbidities. 13 turbidities post Mt. Mazama eruption @ 6845 ± 50 rcybp (Bacon, 1983). There are few age controls on the times and rates of turbidity deposition of the Cascadia Channel. One 14 C date in core 6509-27 (Griggs et al., 1969) for the eighth turbidite @ 4645 ± 190 rcybp also provides some temporal control. This date also correlates with 8th peat at Willapa Bay @ 4290 ± 80 rcybp [sample H1-B, Atwater, 1988] The thickness of pelagic layers between the turbidites and the extent of bioturbation can also be used to establish relative measures of variability of earthquake recurrence times (see discussion for Task 3).

Oregon

- Necanicum
  Darienzo, Peterson and Clough (1994) – 480 ± 60, 800 ± 60; 1100 ± 70; 1370 ±70; 2200 ± 90

- Ecola
  Gallaway et al. (1992) – 380 ±60; 1270 ± 60; 2640 ± 70

- Nehalem River
  Nelson et al., (1995)

- Nestucca Bay
  Darienzo, Peterson and Clough (1994) – 400 ± 60; 1510 ± 90; 1460 ± 70; 1860 ± 70; 2560 ± 70. Huliman 2 core – identifies 12 burial events in 5700 years (475 yr. repeat time) in top 11 m of core. Longest record of buried peats in the Pacific NW.

- Netarts Bay
  Darienzo and Peterson, (1990); Nelson et al., (1995, 1996) – 350 ± 60; 660 ± 60; 1270 ±60; 1670 ± 80; 1840 ± 60; 2600 ± 70

- Siletz
  Darienzo, Peterson and Clough (1994) – 270 ± 60; 350 ± 60; 1330 ± 70; 1510 ± 90; 1690 ± 70; 2550 ± 80

- Yaquina
  Darienzo, Peterson and Clough (1994) – 160 ± 60; 550 ± 70; 1350 ± 60; 1680 ± 70; 2570 ± 70; 2780 ± 70

- Alsea Bay
  Peterson and Darienzo, (1991, 1996) – 160 ± 50; 480 ± 60; 800 ± 80; 1490 ± 80; 2210 ± 80; 2620 ± 60

- Salmon River
  Nelson et al., (1995) – AMS ages on rooted leaves and stems - 157± 17.

- Coos Bay, South Slough
  Nelson, (1992); Nelson et al., (1996); Peterson and Darienzo, (1989) – 140 ± 50; 380 ± 60; 650 ± 70; 1520 ± 60; 1960 ± 60; 2350 ± 90; 2760 ± 80

- Coquille River
  Nelson et al. (1995) AMS ages on rooted leaves and stems - 192± 17.

California

- Mad River Slough -
  Clark and Carver, (1992), Nelson et al., (1995) High precision ages on tree rings – 5 years before tree death – 120 ±8; 40 years before tree death –214 ± 8; 60-80 years before tree death – 282 ± 14; Evidence for 4 to 5 events between 1450 and 1750.

Correlation of Events along the Cascade Subduction Zone

As seen in Table 1, approximately 1/3 of the sites record one, usually the most recent, event along the Cascade subduction zone. The remaining sites contain records of multiple events in the last 3000 years. Currently, only two sites have published radiocarbon ages for events > 3500 years.

The most recent, and best-sampled, event corresponds to the January 1700 earthquake, Atwater's (1997) soil Y, that has been documented with more than 85 radiocarbon ages and tree ring ages (Nelson et al., 1995; Yamaguchi et al., 1997). Within the resolution of the data, this event has been suggested to represent a single great earthquake (or a series of multiple earthquakes, closely spaced in time) that ruptured at least 900 km of the Cascade subduction zone between southern British Columbia and California (see Figure 4).

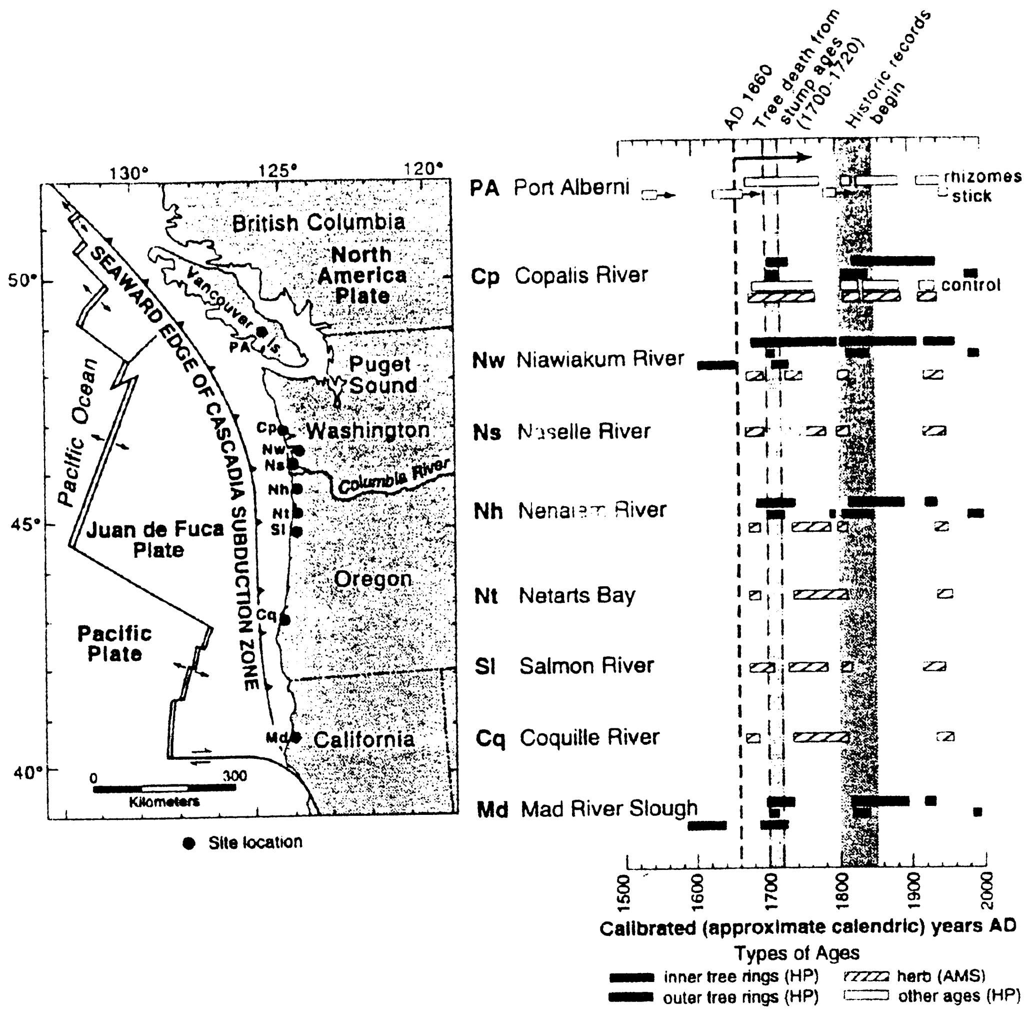

Figure 4 Site map for 14C dating along the Cascades subduction zone (after Nelson et al., 1995). Map, left, shows locations of sites sampled to constrain the date and coastal extent of the January 1700 earthquake. Horizontal bars at right show calendar ages at two standard deviations. Historic records of the past 200 years restrict subsidence to before about 1850 and probably before 1800. Shaded interval between 1700 and 1720 shows likely time of subsidence.

Using the selection criteria discussed in the previous section,, Nelson et al (1996 a,b) identify a second regional submergence event at ~1700 ybp for 4 sites along the Washington-Oregon coastline [Niawiakum River, Naselle River, Netarts Bay and Coos Bay). This second event correspond to Atwater's (1997) soil S (1500-1700 ybp), which is the most conspicuous of all buried soils in many Washington coastal outcrops. This event has been tentatively identified as far north as the Copalis River and as far south as Humboldt Bay in California.

A third, widespread event at 2400-2700 ybp is also evident in Table 1, and corresponds to soil N of Atwater (1997) at Willapa Bay and Grays Harbor, and straddles two events identified at Coos Bay, 2300 and 2760 ybp.

All three of these widespread events have been highlighted in Table 1.

Between these three events, the evidence for a coseismic origin is more equivocal. The lack of strong lithologic contrasts and evidence for >1/2 m submergence make regional correlations more tenuous. Moderate magnitude, intraplate events can produce localized deformation unrelated to larger scale interplate activity. Nelson and Personius (1997) recognize that the paleoseismic record at Coos Bay is a composite of both regional and local earthquakes, which represent a record of both interplate and intraplate activity.

In addition to identifying events or episodes of subduction with widespread temporal correlation, we have also identified a more discontinuous episode of seismic activity along the Cascades subduction zone between 1000 and 1700 ybp. As seen in Table 1, the period from 1700 to 1300 ybp is more active than the period from 1300 to 1000 in southern Oregon,. In contrast, radiocarbon ages indicate that northern Oregon and southern Washington experienced more seismic activity between 1300 to 1000 ybp. This apparent temporal transition is spatially coincident with change in structural style as represented by regional patterns of marsh stratigraphy and possible segmentation of the Cascades margin at 44 – 45N (Nelson and Personius, 1996).

Based on the analysis of data collected for this project task, we feel that additional study will be needed to establish paleoseismic benchmarks at various sites along the coast for pre-1700 events. Southern Washington is already a benchmark, owing to its fine outcrops, micropalentology, and high-precision radiocarbon dating described in Atwater and Hemphill-Haley (1996). In general, only multiple AMS and high-precision ring-wood ages are precise enough for correlation from one estuary to another. At the time this project was proposed, both groups of investigators believed that paleoseismic records in south-central Oregon would be of a comparable level of resolution to those in Washington, and be in the published literature. Subsequent conversations with Harvey Kelsey, Alan Nelson, and Brian Atwater however, indicate that publishable results from Oregon are still one or two years into the future.

Table 1 Regional correlation of paleoearthquakes and subsidence events along the Cascades subduction zone. Stratigraphic sections for 20 sites along the Cascades subduction zone, from Vancouver, British Columbia to northern California are compared in a spreadsheet format to determine the coastal extent of buried soils and inferred earthquake ruptures. Vertical gray shaded boxes represent ^{14}C ages (in radiocarbon years before present, AD 1950) ±1 standard deviation for individual events discussed in the text. Horizontal blue shaded sections represent age ranges of individual events identified in southern Washington (after Atwater and Hemphill-Haley, 1996 and Table 3(this report)). Evidence for both widespread regional events as well as more localized events that may represent either inter- or intraplate ruptures. (See Table in pocket at back of report)

Project Task 3 – Improve Earthquake Recurrence Models and Refine Earthquake Probability Estimates

Early estimates of earthquake recurrence models and the probabilities for the occurrence of great earthquakes along the Cascades subduction zone were based on preliminary data that was available a decade ago. Nishenko (1989, 1991), using conventional ^{14}C estimates for seven events and the apparent aperiodic nature of interevent times in southern Washington, used a Poisson model and an average interevent time of 500 to 600 years for his estimate of 0.02 in 10 years. Adams (1990), using 13 turbidite layers in the Cascades Channel and a recurrence period of 590 ± 170 years, proposed a normal or Gaussian probability distribution for his estimate of 0.10 in 100 years.

Since these early studies, several sites with long (>5000 year) earthquake histories have been identified in the Pacific Northwest, including -

- A 7500 year record of tsunami deposition in a freshwater lake along coastal Oregon, near Cape Blanco, is one of the longest records of tsunamis along the Cascades subduction zone. Nelson et al. (1996) identified 14 events in 7500 years at Bradley Lake to estimate a 535 year average repeat time.

- A 5700 year record of buried peats at Nestucca Bay, Oregon is the longest record of its kind in the Pacific Northwest. 12 events were identified in 5700 years, a 475-year average repeat time. (Hurliman 2 core, Darienzo, Peterson and Clough (1994)). The five most recent events are discussed in the more detail under Task 2.

These and other estimates are summarized in Table 2.

Table 2 Long-Term Average Recurrence Times for the Cascadia Subduction Zone

Author	Location	Range of Intervals	Average Interval
Atwater and Hemphill-Haley (1996)	southern Washington	300-1200	500-540
Peterson and Darienzo (1996)	central Oregon	300-700	400+
Clark and Carver (1991)	Northern California	150-500	500
Adams (1990)	Cascadia Channel		590 ± 170
Nelson (1996)	Bradley Lake, OR		535
Darienzo, Peterson and Clough (1994).	Nestucca Bay, OR	50-1000	475-560
Nelson et al (1996)	Coos Bay, OR	500-1500	(min 500)
Shennan et al (1996)	Grays Harbor, WA		670-730

All three sites (Cascades Channel, Hurliman 2 and Bradley Lake) indicate long-term averages between 475 and 590 years. These long-term rates are consistent with those used by Nishenko (1989, 1991) and Adams (1990). What these long-term rates do not address, however, is the variability of the individual recurrence times with respect to the mean or average repeat time. This variation can be expressed in terms of the coefficient of variation (COV), which is the ratio of the standard deviation to the mean. COV values near 1.0 imply clustered recurrence behavior, while values significantly less than 1.0 imply quasi-periodic recurrence behavior. Coefficients of variation for seismic zones in the circum-Pacific seismic region have been reported in the range 0.2 to 0.4 (Nishenko and Buland, 1987; Ellsworth, 1995).

This Project Task concentrates on modeling observed recurrence time behavior using a suite of failure time distributions including Beta, Weibull, and Poisson. These distributions are in turn used to develop probability (and uncertainty) estimates for the recurrence of similar events in the next 50 years. For the statistical analysis in this Task, we have use the paleoearthquake record from southern Washington (see Table 3, after Atwater and Hemphill-Haley, 1996). These ages are also highlighted in Table 1, for comparison with other ^{14}C ages along the Cascades subduction zone. Radiocarbon ages were converted to calendar ages and probability densities using Oxcal version 2.18 (http://units.ox.ac.uk./departments/rlaha/oxcal/oxcal.html) and the calibration data of Stuiver and Becker (1993).

Table 3 Ages of major earthquakes in southern coastal Washington during the last 3500 years.

Soil	Age Dating Control	Date, calendric years before AD 2000	Reference
Y	11 high precision ages on inner and outer rings of spruce roots in soil.	280-300	Atwater et al. (1991) Nelson et al., (1995)
W	5 conventional ages- peat at Grays Harbor; spruce root at Willapa Bay; sticks and shrub root at Columbia River	900-1300	Atwater, 1992
U	2 high precision ages from Willapa Bay . *Salicornia virginica* stems rooted in soil (1260 ± 14 14C yr BP, QL-4795). *Triglochin maritima* rhizomes 20 cm above soil (1302±21 14C yr BP, QL-4798)	1130-1350	Atwater and Hemphill-Haley (1996), Atwater et al, in prep.
S	2 high precision ages from Willapa Bay, *Triglochin maritima* rhizomes 45-55 cm above soil (1598±23 ^{14}C yr BP, QL-4797), wood 60-69 rings from bark of red cedar in soil (1740±15 ^{14}C yr BP, QL-4796).	1500-1700	Atwater and Hemphill-Haley (1996) Atwater et al, in prep.
N	High-precision ages of forest-floor litter on soil	2400-2780	Atwater and Hemphill-Haley (1996)
L	12 conventional ages among five localities at Grays Harbor and Willapa Bay + stratigraphic bracketing between soils J and N	2400-3500	Atwater, 1992; Atwater and Hemphill-Haley (1996); Shennan et al., (1994)
J	Weighted mean of 3 high-precision ages on forest floor litter on soil	3320-3500	Atwater and Hemphill-Haley (1996) Atwater et al, in prep.

The seven events that have been identified in the last 3500 years are defined as either representing a single great earthquake or a series of great earthquakes that occurred too close in time for geologic dating to resolve. These seven events define six time intervals of unequal length that average 500 to 533 years. Similar to the >5000 year records discussed above. Two of those intervals are close to 1000 years long, while the remaining four are less than 500 years long. The relatively long recurrence intervals are supported not only by radiocarbon dating, but by paleoecology and tree-ring counts as well. In other words, these long intervals do not appear to be the product of 'missed' events. During intervals N-S and W-Y, forests replaced tidal marshes more widely than at any other time in the last 3500 years. These forests are marked by growth position tree stumps, upland diatom assemblages and deep weathering profiles in underlying tidal deposits. Some of the stumps contain hundreds of annual rings, even in areas where tidal marshes have become forest in the 300 years since event Y. The forests from intervals N-S and W-Y imply prolonged emergence, that like much of modern coastal uplift at Cascadia, probably resulted from shortening of the North American plate above a locked subduction zone.

Evidence for irregularity of recurrence intervals may also be recorded in the Cascades Channel turbidite deposits that were previously thought to be indicative of more periodic recurrence behavior. Successive turbidites in the Cascades Channel differ in depth and abundance of animal burrows, which correlate among core over 100 km of the channel. Animal burrows in marine deposits commonly deepen and multiply over time. As seen in Figure 5, the variation in the concentration of burrows resembles the pattern implied by the radiocarbon ages and former forests in coastal Washington, except for the poorly measured intervals J-L and L-N. Adams (1990, 1996) previously inferred regularity from similarities in thickness among pelagic beds between successive turbidites. Each pelagic bed, however, may have been deeply eroded by successive turbidity currents.

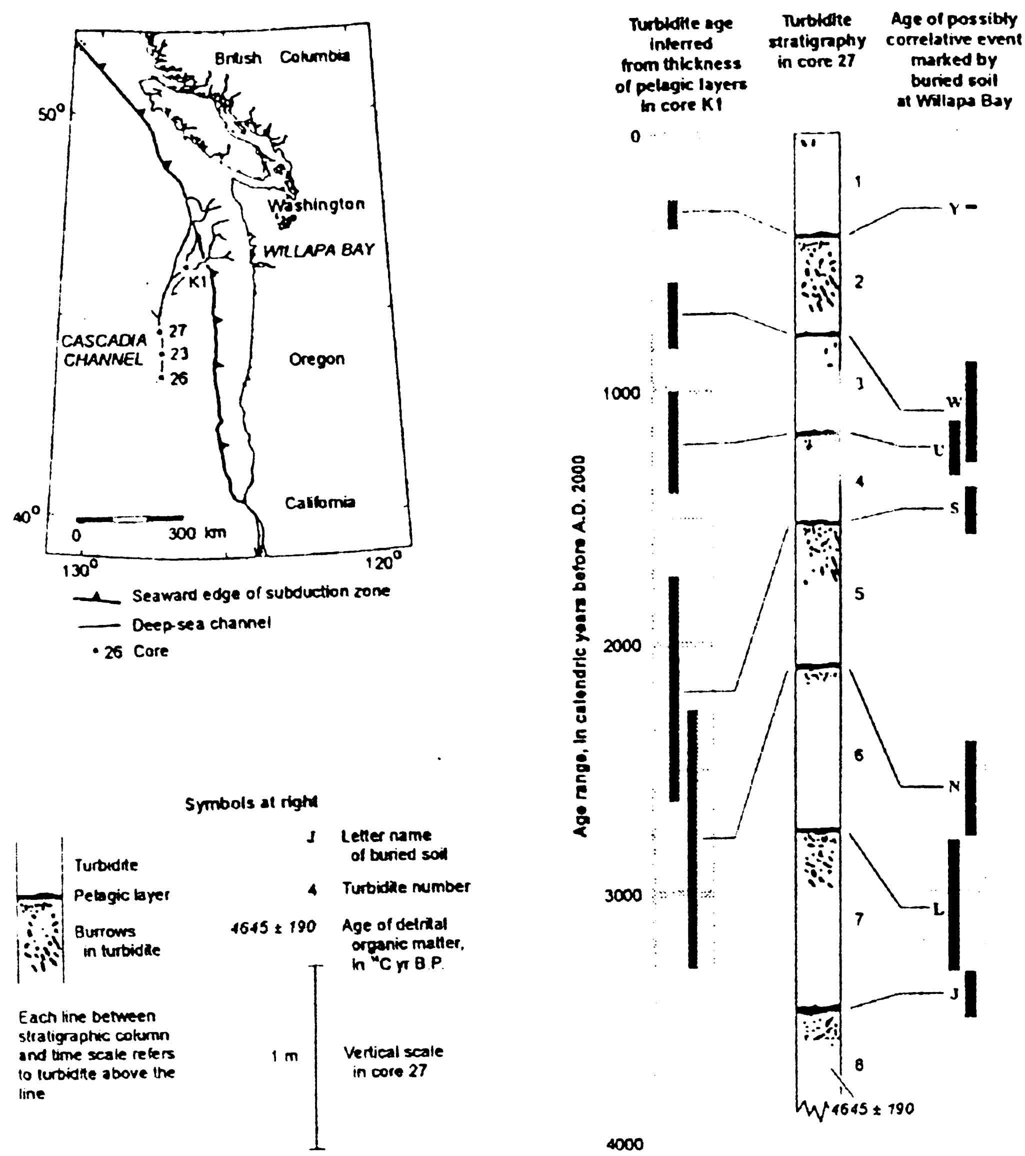

Figure 5 Correlations of turbidite stratigraphy in Cascadia Channel with buried soils in Willapa Bay. Map at left shows location of cores in Cascadia Channel. Section at right shows correlation of stratigraphy in core 27 with ages inferred from the thickness of pelagic layers in core K1 with calendric ages of buried soils form Willapa Bay. Variation in the concentration of burrows resembles patterns implied from radiocarbon ages of soils – long intervals between events associated with deeper and better developed animal burrows.

While the six observed intervals from coastal Washington can be used to estimate the probability of the next event, some caveats are in order. Most historic and geologic based determinations of seismic hazard are plagued by small sample sizes. For example, the historic record of great earthquakes in southwestern Japan contains six events in 1300 years, and the 2000 year paleoseismic record for the San Andreas fault in southern California contains nine recognized intervals. These small samples of earthquake activity influence the ability to estimate recurrence distributions and recurrence times with great confidence. Prior attempts to deal with this problem have used *ad hoc* and 'generic' recurrence models (Nishenko and Buland, 1987; Ellsworth, 1995). In the case of geologic data, the problem is further exacerbated by including uncertainties as to when the event in question actually occurred.

- Beta Distribution

Savage (1994) applied Bayes' theorem to empirically determine that earthquake probabilities from observed recurrence intervals are beta distributed. P(p|m,n) is the probability density associated with the proposition that p is the probability of rupture of the segment in a specified time interval given that m of n recurrence intervals would predict rupture within that time interval.

$$P(p|m,n) = \{(n+1)!/[(m!(n-m)!]\}p^{m}(1-p)^{n-m}$$

The mean probability, or expected value, is given as

$$\langle p \rangle = (m+1)/(n+2)$$

The maximum likelihood estimate is

$$m/n$$

The variance is given as

$$\sigma^2 = \langle p \rangle \, (1- \langle p \rangle) \,/\, (n+3)$$

As Savage (1994) points out, the uncertainty in p decreases slowly as a function of the number of observations, n. A fivefold increase in the number of recurrence intervals only decreases the uncertainity in the estimated probability by a factor of two. In other words, increasing the length of the earthquake record from 3500 to 17500 years would decrease the uncertainty in our estimate of the mean repeat time by only a factor of 2, all other parameters being fixed.

We have extended this non-parametric method by also incorporating the uncertainties associated with geologically determined intervals into the estimate. Out of the six observed intervals in Figure 6 d-k, 29% of the total area is less than 300 years. 71% of the total area is greater than 300 years, and 10% of the area is in the interval 300 to 350 years since 1700 AD (event Y). Based on the above equations, the mean probability is equal to 0.25 for the interval 2000 – 2050 and the 90% confidence interval is from 0.04 to 0.56. See Table 4. Note, that while the expected value of the beta distribution is 0.25, the maximum likelihood estimate is 0.14, close to the Poisson model estimate discussed below (see Figure 7).

- Weibull Distribution

The Weibull distribution can represent a spectrum of failure time distributions by varying the shape parameter β. Parameters for the Weibull distribution can be defined using least squares techniques. This flexibility helps define the appropriate distribution using available empirical data and is widely used in seismology and engineering applications (e.g., Rikitake, 1976; Kapur and Lamberson, 1977, Nishenko, 1985; Sieh et al., 1989).

The empirical cumulative distribution function is

$$F(t) = 1 - e^{(-t/\theta)\beta}$$

where t is the exposure period, θ is the characteristic life (and is related to the mean recurrence interval $\mu = \theta\Gamma(1+ 1/\beta)$), and β is the shape parameter. For $\beta = 3.5$, the Weibull distribution represents a normal or Gaussian distribution and for $\beta = 1.0$ the Weibull distribution is the exponential distribution. Values for β range from 3 to 5 for sequences of historic great earthquakes on subduction zones in southern Chile and southwest Japan (Rikitake, 1976; Nishenko, 1985), areas that have been proposed a tectonic analogs for the Cascadia subduction zone (Heaton and Hartzill, 1987, 1989))

A least-squares fit to the means of the data in Figure 8 gives a recurrence interval, μ of 538 years and a shape parameter of $\beta = 1.67$. The corresponding conditional probabilities for 20, 50, and 100 year exposure periods are 0.04, 0.09, and 0.17, respectively (see Table 4). Note that the β of 1.67 is not that far removed from $\beta = 1.0$, and the resulting probabilities are not significantly different from hose based on a Poisson model of earthquake occurrence and an exponential recurrence distribution.

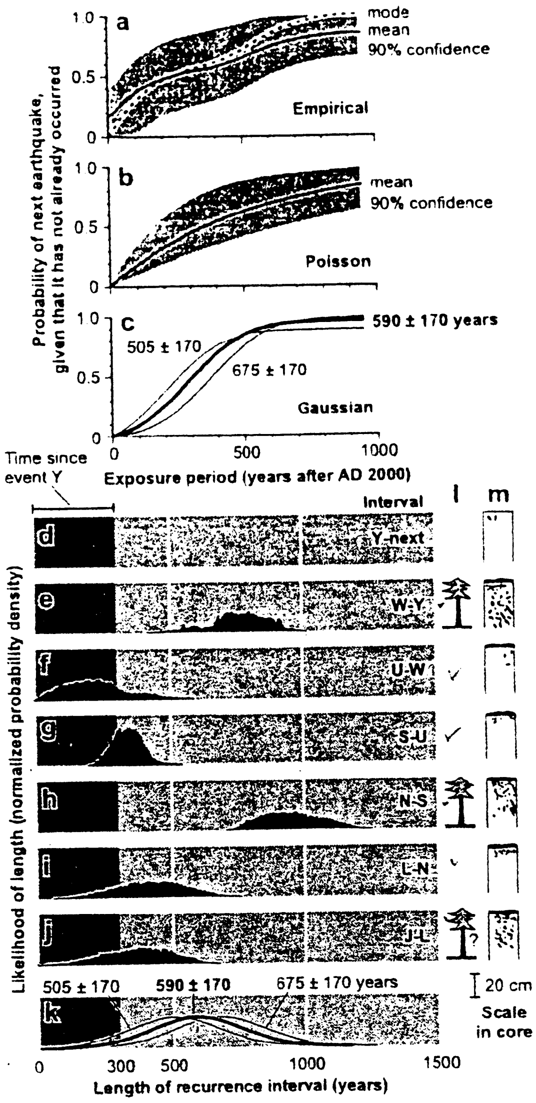

Figure 6 Earthquake probabilities (a-c) and supporting numerical and relative measures of recurrence intervals (d-k). Probabilities in a are based on the numerical intervals in e-j and on the relative intervals inferred from l and m. Diagram b incorporates only a mean interval calculated from the age difference between events J and Y (Figure 2b). Diagram c corresponds to recurrence interval distributions in k, which were inferred from turbidites in the Cascadia Channel (Adams, 1990). In e-j, individual intervals are expressed as normalized probability densities, calculated from differences between the coastal ages shown in Figure 2b. Tree symbol in l denotes intervals during which forests spread widely onto tidal marshes in areas that have not reverted to forest in the 300 years since the last earthquake. The symbol is queried for interval J-L because remains of forest rooted in soil L are too low in the modern intertidal zone to be observed widely. Black dots and ovals in m show depth and abundance of animal burrows in turbidites of Cascadia Channel. Black band represents pelagic mud on top of each turbidite (from sketch of core 27 [see Figure 5] by Griggs et al., 1969).

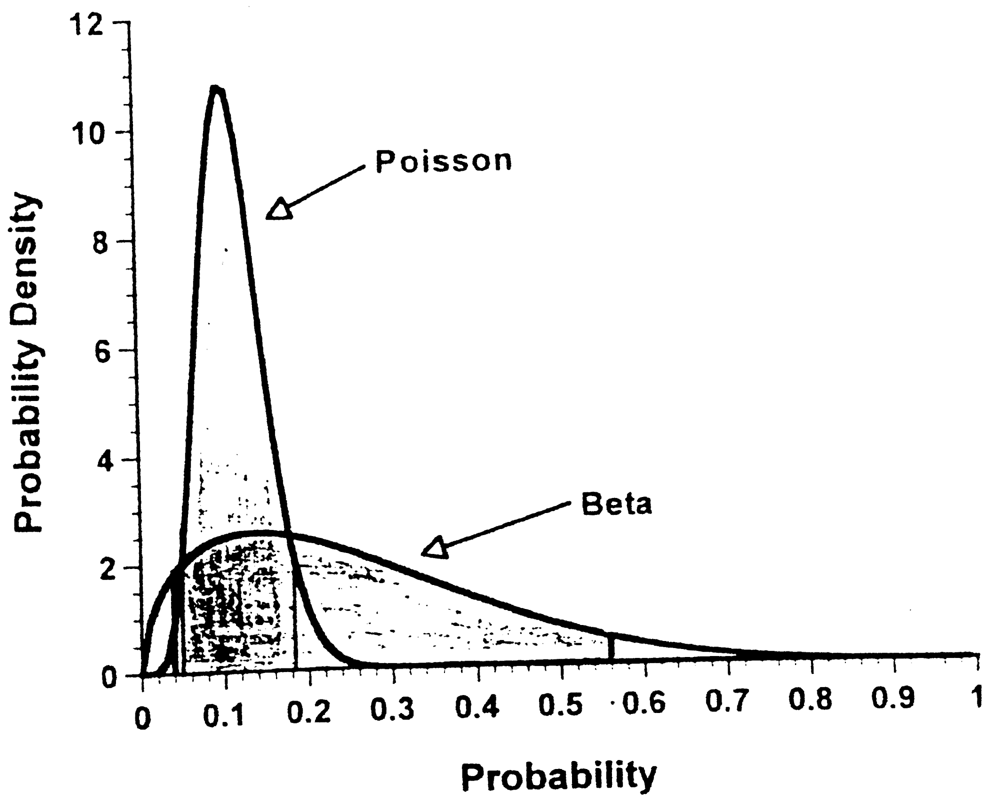

Figure 7 Comparison of probability density functions for Poisson and Beta distributions. Probability density as a function of probability of rupture based on the data in Table 3. Vertical lines show the location of the 0.05 and 0.95 confidence limits for each distribution. With the inclusion of more data, the mean of the beta distribution approaches the maximum likelihood estimate of the mean, which is similar to that of the Poisson distribution.

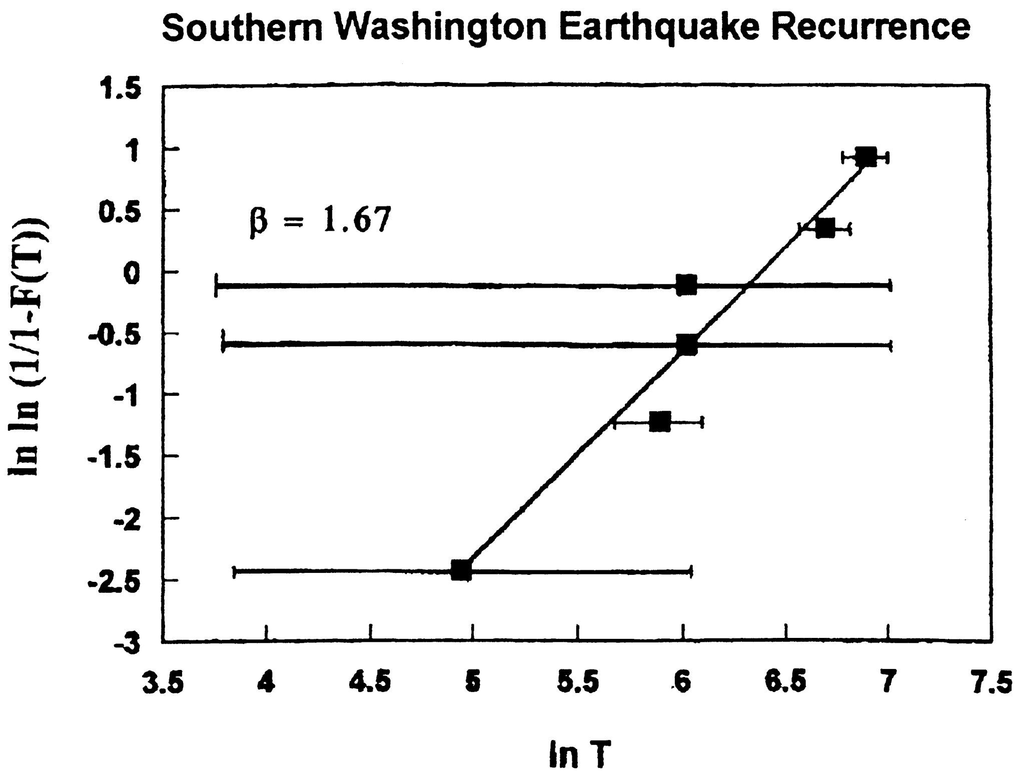

Figure 8 Weibull distribution plot of ln ln (1/1-F(T)) as a function of ln T for Holocene earthquake recurrence intervals in southern coastal Washington (see Table 3 for actual recurrence intervals). Horizontal error bars shown for interevent times are 1-sigma confidence limits. Cumulative distributions [F(T)] are plotted according to a (ni-0.5/N) plotting rule. Least squares fits to the means of the data define the Weibull distribution parameters, β= 1.67 and the mean repeat time = 538 years.

- Poisson Distribution

As mentioned in the previous section, the Weibull shape parameter β has a value that is close to that of an exponential distribution. This result motivates our further discussion of the Poisson distribution. The Poisson model assumes that earthquakes are independent in space, time and magnitude, and that the probability of an event during a time interval is proportional to the length of the time interval. The memoryless property of a Poisson model, constant hazard as a function of the time elapsed since the last event, also serves a useful benchmark for comparison to the time dependent models discussed in this study.

The maximum likelihood estimate of the mean life, θ, for an exponential distribution is

$$\theta = T/r$$

where T is the period of observation and r is the number of events during that period (e.g. $\theta = 500$ years for $r = 7$ events in $T = 3500$ years). Note this is slightly less than the Weibull mean life estimate of 538 years. Poisson probabilities estimated from a mean recurrence time of 538 years (using the Weibull analysis) are 0.04, 0.09 and 0.18, for exposure times 20, 50, and 100 years, respectively. Probabilities based on the maximum likelihood estimate of 500 years are 0.039, 0.095, and 0.18 for exposure times 20, 50, and 100 years, respectively.

The $100(1-\alpha)\%$ confidence limits for the mean life, θ, of a Poisson distribution are

$$2T/\chi^2_{\alpha/2,\,2(r+1)} < \theta < 2T/\chi^2_{1-\alpha/2,\,2r}$$

or

$$2T/\chi^2_{(0.05,\,16)} < \theta < 2T/\chi^2_{(0.95,\,14)}$$

90% confidence limits for the above θ values range from 266 to 1065 years, and corresponding Poisson probabilities for a 50-year exposure time range from 0.046 to 0.171. These limits can also be expressed in terms of the number of events, and are rather broad, 3 to13 events in 3500 years (Beyer, 1985; Pearson and Hartley, 1956). The corresponding range in probabilities at the 10 percent significance level are 0.02 – 0.07, 0.04 – 0.17, and 0.08 – 0.31 for 20, 50, and 100 year exposures, respectively (see Table 4).

As seen in Table 5, these estimates are higher than those previously published for the Cascades region. Recognition and quantification of the uncertainty in our estimate is an important component to developing a realistic seismic hazard assessment for the Cascade subduction zone. While our best, unbiased estimate (0.25 in 50 years) is associated with a large uncertainty (0.04 to 0.57) it does provide a valuable baseline for future scientific research and public safety and engineering decisions.

Table 4 Summary of Probability Estimates

Distribution	Equation	Parameters	P_{50}	90% Confidence Limit
Beta	$(m+1)/(n+2)$	m = 0.59, n = 4.27 *	0.25	0.07 – 0.57
		m =0, n = 5	0.14	0.00 – 0.32
		m =1, n =5	0.29	0.02 – 0.46
		m= 2, n =5	0.43	0.09 – 0.57
Weibull	$1 - e^{(-t/\theta)\beta}$	θ =538, β= 1.67	0.09	
Poisson	$1\text{-}\exp^{(-[t2-t1]/\mu)}$	μ =500	0.095	0.046 –0.17
Gaussian	$P(t_2\text{-}\mu/\sigma) - P(t_1\text{-}\mu/\sigma)$	μ =590, σ =170	0.04	0.02 – 0.07

Beta distribution: m, the number of recurrence intervals that end between times t1 and t2. n, the number of intervals longer than t_1. m and n values marked with * are the sum of areas under the distribution curves in Figure 6 for recurrence intervals between 300 and 350 years and intervals longer than 300 years.
Weibull distribution: see Figure 8, based on Table 3
Poisson distribution: μ, the maximum likelihood estimate of the mean based on buried soils from Table 3.
Gaussian Distribution: μ, the mean interval. σ, the standard deviation of intervals (based on turbidite data from Adams (1990, 1996).

Table 5 Published Probability Estimates for the Cascadia Subduction Zone

Author	Recurrence Model	Recurrence Time	10 yr	20 yr	50 yr	100 yr
Nishenko (1989)	Poisson	500-600	0.02			
Adams (1990, 1996)	Gaussian	590 ± 170			0.05	0.10
This study (1999)	Weibull	538		0.04	0.09	0.17
"	Beta				0.25	
"	Poisson	500	0.02	0.04	0.09	0.18

References

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone- evidence from turbidites off the Oregon-Washington margin, *Tectonics*, **9**, 569-583.

Adams, J., 1996, Great earthquakes recorded by turbidites off the Washington-Oregon coast in, A.M. Rogers, T.J. Walsh, W.J. Kockelman, and G.R. Priest, eds., Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest, *USGS Prof. Paper 1560*, 147-158.

Ando, M., 1975, Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan, *Tectonophysics*, **27**, 119-140.

Atwater, B., et al., (including S. Nishenko), 1998, Irregular recurrence of great earthquakes along the Cascades subduction zone, in prep.

Atwater, B. et al., (including Nishenko, S.), 1995,Summary of coastal geologic evidence for past great earthquakes along the Cascades subduction zone, *Earthquake Spectra*, **11**, 1-18.

Atwater, B. and Hemphill-Haley, E., 1997, Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington, U.S. Geological Survey Prof. Paper 1576, 108 pp.

Atwater, B., 1988, Geologic studies for the seismic zonation of the Puget lowland, in Jacobson, M.L. and Rodriguez, T.R., eds., National Earthquake Hazard Reduction Program, Summaries of technical reports, Volume XXV, *US Geological Survey Open File Rpt. 88-16*, 120-133.

Bacon, C.R., 1983, Eruptive history of Mt. Mazama and Crater Lake caldera, Cascade Range, USA, *Volcanology and Geothermal Research Journal*, **18**, 57-115.

Beyer, W.H., 1985, CRC Handbook of Tables for Probability and Statistics, 2nd ed., CRC Press, Boca Raton, Florida

Clague, J.J., Naesgaard, E., and Nelson, A.R., 1997, Age and significance of earthquake induced liquefaction near Vancouver, British Columbia, Canada, *Canadian Geotechnical Journal*, **34**, 53-62.

Darienzo, M.E., Peterson, C.D., and Clough, C., 1994, Stratigraphic evidence for great subduction zone earthquakes at four estuaries in northern Oregon, *Jour. Coastal Research*, **10**, 850-876.

Ellsworth, W.L., 1995, Characteristic earthquakes and long-term earthquake forecasts: implications for central California seismicity, in Cheng, F.Y. and Sheu, M.S., eds., Urban Disaster Mitigation: the role of Science and Technology, Elsevier Science Ltd., p.1-14

Gallaway, P.J., Peterson, C.D., Watkins, A.M., Craig, S. and McLeod, B.L., 1992, Paleo-tsunami inundation and runup at Cannon Beach, Oregon. *Final Report to the Clatsop County Sheriffs Office*, 36 pp.

Griggs, G.B. and Kulm, L.D., 1970, Sedimentation in the Cascadia deep-sea channel, *Geol. Soc. America Bull.*, **76**, 675-708.

Griggs, G.B., Carey, A.G. and Kulm, L.D., 1969, Deep-sea sedimentation and sediment fauna interaction in Cascade channel and on Cascade abyssal plain, *Deep Sea Research*, **16**, 157-170.

Heaton, T.H. and Hartzell, S.H., 1987, Earthquake hazards on the Cascadia subduction zone, Science, 236, 162-168.

Heaton, T.H. and Hartzell, S.H., 1989, Estimation of strong ground motions from hypothetical earthquakes on the Cascadia subduction zone, *Pure Applied Geophys.*, **129**, 131-201.

Jacoby, G.C., Bunker, D.E., and Benson, B.E., 1997, Tree-ring evidence for an AD 1700 Cascadia earthquake in Washington and northern Oregon, *Geology*, **25**, 999-1002

Kapur, K.C., and Lamberson, L.R., 1977, Reliability in Engineering Design, Wiley, New York, 586 p

Nelson, A.R., Atwater, B.F., Bobrowsky, P.T., Bradley, L-A, Clague, J.J., Carver, G.A., Darienzo, M.E., Grant, W.C., Krueger, H.W., Sparks, R., Stafford, T.W., and Stuiver, M., 1995, Radiocarbon evidence for extensive plate boundary rupture about 300 years ago at the Cascade subduction zone, *Nature*, **378**, 371-374.

Nelson, A.R. and Personius, S.F., 1996, Great earthquake potential in Oregon and Washington – an overview of recent coastal geologic studies and their bearing on segmentation and Holocene ruptures, central Cascadia subduction zone, in , A.M. Rogers, T.J. Walsh, W.J. Kockelman, and G.R. Priest, eds., Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest, *USGS Prof. Paper 1560*, 91-114.

Nelson, A.R., Jennings, A.E. and Kashima, K., 1996, An earthquake history derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon, *Geol. Soc. America Bull.*, **108**, 141-154.

Nelson, A.R., Shennan, I. and Long, A.J., 1996, Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascade subduction zone of western North America, *Jour. Geophys. Res.*, **101**, 6115-6135.

Nelson, A.R., Kelsey, H.M., Hemphill-Haley, E., and Witter, R.C., 1996, A 7500 yr. lake record of Cascadia tsunamis in southern coastal Oregon, in *Geol. Soc. America Abstracts with Programs*, **28**,

Nishenko, S.P., 1991, Circum-Pacific seismic potential – 1989-1999, *Pure Applied Geophys.*, **135**, 169-259.

Nishenko, S.P. 1989, Circum-Pacific seismic potential – 1989-1999, *USGS Open File Rpt. 89-* ,

Nishenko, S.P., 1985, Seismic potential for large and great interplate earthquakes along the Chilean and southern Peruvian margins of South America – a quantitative reappraisal, *Jour. Geophys. Res.*, **90**, 3589

Ota, Y,M., Nelson, A.R., Umitsu, M., Kaoru, K. and Matsushima, Y., 1995, Interpreting an earthquake history from the stratigraphy of late Holocene intertidal deposits in South Slough, Coos Bay, Oregon, USA, *Jour. Geol. Soc. Japan*, **104**, 94-106

Pearson, E.S. and Hartley, H.O. , 1956, Biometrika Tables for Statisticians, Cambridge Univ. Press, New York

Peterson, C.D. and Darienzo, M.E., 1996, Discrimination of climactic, oceanic, and tectonic mechanisms of cyclic marsh burial, Alsea Bay, Oregon, in , A.M. Rogers, T.J. Walsh, W.J. Kockelman, and G.R. Priest, eds., Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest, *USGS Prof. Paper 1560*, 115-146.

Rikitake, T.(1976), *Tectonophysics*, **35**, 335.

Satake, K., Shimazaki, K., Tsuji, Y. and Ueda, K., 1996, Time and size of a great earthquake in Cascadia inferred from Japanese tsunami record of January 1700, *Nature*, **379**, 246-249.

Savage, J.C., 1994, Empirical earthquake probabilities from observed recurrence intervals, *Bull. Seismol. Soc. America*, **84**, 219-221.

Shennan, I., Long, A.J., Rutherford, M.M., Green, F.M., Innes, J.B., Lloyd, J.M., Zong, Y., and Walker, K.J., 1996, Tidal marsh stratigraphy, sea-level change and large earthquakes 1: a 5000 year record in Washington, USA, *Quaternary Science Reviews*, **15**, 1023-1059.

Sieh, K., et al., 1989, *Jour. Geophys. Res.*, **94**, 603

Stuiver, M., and Becker, B., *Radiocarbon*, **35**, 35-67.

Thatcher, W., 1990, Order and diversity in modes of circum-Pacific earthquake recurrence, *Jour. Geophys. Res.*, **95**, 2609-2624

Yamaguchi, D., Atwater, B.F., Bunker, D.E., Benson, B.E., and Reid, M.S., 1997, Tree-ring dating the 1700 Cascadia earthquake, *Nature*, **389**, 922.